Whole-Building Simulation of Hybrid Ventilation based on Full-scale Measurements in an Institutional High-rise Building for Predictive Control

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Abstract

Hybrid ventilation is an effective approach to reduce cooling energy consumption by combining natural and mechanical ventilation. Full-size and whole-building measurements of high-rise hybrid ventilation are quite limited in the literature due to the challenges associated with the complexities of the building and variable ambient conditions. Because of limited measurement data, validated and accurate whole-building simulations of hybrid ventilation cannot often be found in the literature. This paper reports a series of full-scale measurements of hybrid ventilation in a 17-story institutional building and associated whole-building simulations using both a 15-zone detailed and a 5-zone simplified multizone models. The paper is one of the first studies with real-world and full-scale test data of high-rise hybrid ventilation, which shares key operational and performance experience and case studies of hybrid ventilation with other researchers. Both the test data and the validated simulation models can be used for the comparison and validation of simulation models. It is also shown that the 5-zone simplified model developed from this study is able to model such a complex high-rise building by only a few zones, making possible the on-line model predictive control of a high-rise building. This was illustrated here by an example of optimizing the uniformity of the hybrid ventilation on different floors by modifying inlet areas.

Introduction

The building sector, including residential, commercial and institutional buildings, accounts annually for about 41% of the primary energy usage, 47% of which is used by the space heating and cooling system in the US (DOE 2012). In Canada, more than 55% of the residential sector's total annual energy consumption is for space heating and cooling (OEE 2011). As one of the effective measures to reduce cooling energy consumption, hybrid ventilation combines the benefits of natural and mechanical ventilation and it could reduce cooling load significantly when it is used appropriately (Menassa, Taylor, and Nelson 2013; Malkawi et al. 2016). Many previous studies have been conducted on hybrid ventilation systems. Brohus et al. evaluated hybrid ventilation performance in a four-story office building by the measurements of temperatures, CO_2 levels, and energy consumption (Brohus et al. 2003). Turner and Awbi investigated the thermal performance of hybrid ventilation system and assessed its potential to reduce cooling load through experiments in a room (Turner and Awbi 2015). Menassa et al. conducted a case study in a four-story laboratory building with hybrid ventilation system by on-site measurements under different control strategies. They found that the hybrid ventilation system could achieve an average of 56% energy savings for a best control strategy (Menassa, Taylor, and Nelson 2013). To promote hybrid ventilation as an energy efficient cooling solution to avoid building overheating, IEA EBC Annex 62 "Ventilative Cooling" is developing a database of ventilation cooling applications including a number of buildings with different ventilation systems in various countries (Venticool 2016).

Most of these previous researches focused on single houses or low-rise buildings and a full-scale hybrid ventilation study, especially on-site measurements in actual high-rise buildings, is rather limited. Although the IEA EBC Annex 62 includes a series of different buildings, there is still a lack of whole-building and full-scale data for high-rise buildings with hybrid ventilation. On the other hand, a high-rise building often consumes more energy than low-rises, and its mechanical system is more complex. It is still a challenge how to optimally operate a high-rise hybrid ventilation system under variable weather conditions while keeping acceptable comfort conditions.

Predictive controls based on simulation models, i.e. model predictive controls (MPC), have been shown to be very effective to ensure the performance of a hybrid ventilation system, especially under a variable ambient environment (Hu and Karava 2014). However, it is not practical to use a detailed model of considering all the complexities of the building including its interior structure, thermal mass, mechanical system, cooling/heating loads, and weather conditions, for implementing MPC in a real building (so-called on-line MPC), because MPC often requires certain level of simplifications of the building so it can be easily implemented and used for on-line controls. Therefore, there is a need for research to develop a relatively simple and practical model for MPC that can easily be calibrated, while capturing the essential airflow and thermal physics of hybrid ventilation at an adequate level for achieving its on-line operations.

To address these research needs, this paper presents a full-scale measurement study in a 17-story institutional high-rise building with hybrid ventilation system (Karava et al. 2012; Yuan et al. 2016), and a simple hybrid ventilation model based on the method of multizone airflow network. Measurements including mechanical fan flow rates, ambient temperatures and wind conditions, natural ventilation rates at different floors were conducted for two

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different days. In the present paper, the building was first simulated by a detailed 15-zone multizone model using CONTAM, one of the most popular programs to model ventilation for different types of buildings (Walton and Dols 2013; Qi, Wang, and Zmeureanu 2014; Qi, Wang, and Zmeureanu 2015). The detailed model includes 5 stacked 3-story atriums and defines each floor as one zone exclude the 1st floor and 17th floor that do not have inlets. Based on the detailed model, a simplified 5-zone model is developed and validated by comparing the results to those of the detailed model and the measurement data. An example of using the simplified model is then illustrated for the optimization of the hybrid ventilation of the full-size building.

Full-scale measurements

The measurements were conducted in a 17-story institutional high-rise building located at the downtown Montreal, Canada (45.5°N, 74°W). The building is with two main large facades facing approximately southwest and southeast respectively. The total floor area is about 53,000 m^2. The hybrid ventilation system in the building comprises five vertically-stacked atriums, inlet motorized dampers at both ends of the corridor at each floor, and variable speed mechanical fans at the roof (Figure 1). The five atriums in the buildings are from the second to the sixteenth floor, spanning three floors each (note: floor 17 is the mechanical room). They are separated with a floor slab and connected with 4-m^2 floor grilles with motorized dampers. The dimensions of each atrium are 9 m (W) × 12 m (L) × 12 m (H). The atrium is used as a solar chimney in the hybrid ventilation mode (Tzempelikos, Athienitis, and Karava 2007). The area of the inlet dampers is about 1.4 m^2 when fully opened but can be adjusted by motors.

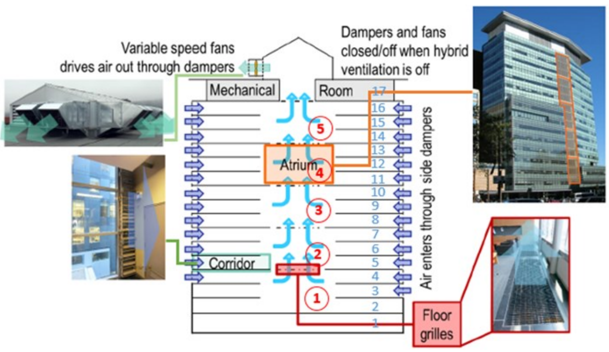

Figure 1: Schematic of hybrid ventilation system in a 17-story institutional high-rise building (Yuan 2016).

The measurements were conducted on two different days. Weather conditions, including wind speed and direction, and outdoor temperature, were measured by a weather station at the roof (Table 1). Though the outdoor temperature was as low as less than 2 °C in Day 1, the cool air was warmed as it flows deeper into the building due to mixing with the indoor environment, and was around 22°C at the atriums. Since there were few occupants near the inlets, no complaints were reported. Note that due to the different weather conditions and potentially different stack effects, the airflow rate of the roof fans are different even at the same fan frequency, e.g. 40% fan frequency in Day 1 and Day 2 (Table 1). Except the fan frequency, all the other data are averaged over time. Table 2 shows the opening area percentage of the inlet dampers for natural ventilation: they were fully open on Day 1 but closed for the floors 2, 3, 14-16 on Day 2.

Table 1: Measurement conditions.

Day	Roof fan frequency (%)	Roof fan flow rate (L/s)	Outdoor temperature (°C)	Wind speed (m/s)
Day 1	20	17291	1.45	3.55
	40	24325	1.70	2.84
	60	31810	1.35	1.54
	80	36707	1.85	1.21
Day 2	40	18117	14.64	1.80

Table 2: Inlet dampers opening percentage.

Floor section	1	2	3	4	5
Day 1	100%	100%	100%	100%	100%
Day 2*	90%	40%	65%	100%	/

* Dampers on floors 2, 3, 14-16 were closed.

Figure 2: Weather station on the roof.

Natural ventilation velocities near the inlet dampers were measured by hot-wire anemometers with sampling time of 60 seconds, and collected by a data logger (Omega HHF-SD1) as shown in Figure 3. The measurement range of the air speed is 0.2 ~ 25 m/s and the accuracy is ± (5%+0.1 m/s). The velocity was measured only for the 5th floor on Day 1 and for the 5th, 8th and 11th floors on Day 2. The velocity measurements were then used to calculate mass flow rates through the inlet damper based on their effective opening areas. More measurement information can be found from our previous studies (Yuan et al. 2016; Yuan 2016; Karava et al. 2012).

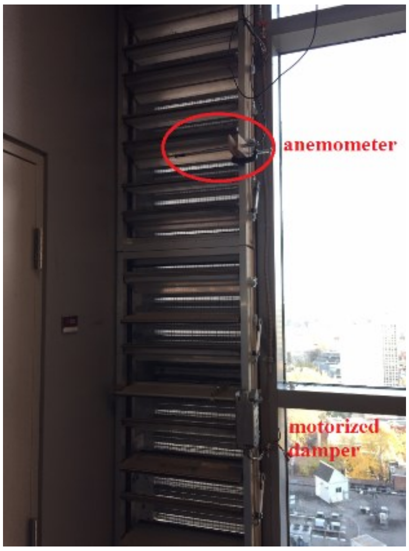

Figure 3: Natural ventilation velocity measurement near inlet dampers.

Simulation

Figure 4 shows a schematic of the detailed simulation model in CONTAM, which includes all corridors, dampers, offices, atriums, stairwells and elevator shafts. Since this detailed model was based on the floors, there is a total of 15 sections (1st floor and 17th floor are not included since they do not have inlets). Based on the number of atrium sections, a simplified model is developed to model each atrium as one zone, so there are five zones for the simplified model, i.e. the so-called 5-zone model.

Mass flow rate through each inlet damper is one of the key parameters for a hybrid ventilation system because it indicates the amount of free cooling available from natural ventilation. In CONTAM, it is modeled by Eq. (1), the power-law flow model (Dols and Polidoro 2015), with the flow exponent, n = 0.5 in this study. $\dot{m}$ is the mass flow rate in kg/s; ρ_0 is the outdoor air density, kg/m^3; Δp is the pressure difference across the damper, Pa; C is the flow coefficient, m^2, which is an empirical parameter determined by the flow resistance of the building structure, and ambient condition etc. Therefore it is necessary to calibrate the flow coefficient, C, for a specific building under certain weather conditions. In this study, the flow coefficient, C, was calibrated by comparing the simulated and measured mass flow rates for the tests on both days.

$$\dot{m} = C\sqrt{\rho_0}\left(\Delta p\right)^n \quad (1)$$

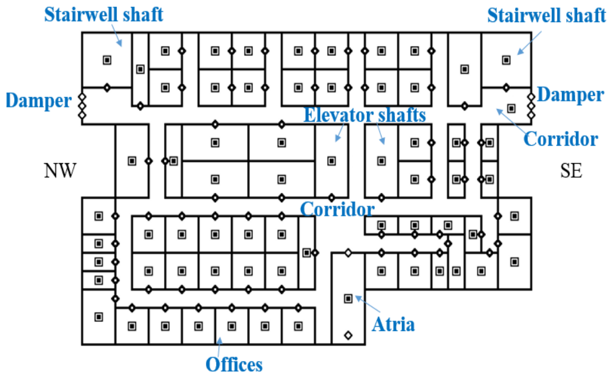

Figure 4: The detailed CONTAM simulation model.

Results

By definition, the value of the flow coefficient, C, is empirical and variable with different weather conditions. In this study, the flow coefficients were calibrated and obtained for both days of tests. In this section, the results of the calibration are first presented for both Day 1 and 2, and followed by a comparison study of the detailed model and the simplified 5-zone model for Day 1.

Simplified model calibration in Day 1

In Day 1, the inlet damper velocity at the 5th floor was monitored under different desired flow rate settings (frequency setting of the variable speed drive) of the roof fan. Figure 5 compares the corresponding inlet natural ventilation flow rates between the measurements and the simulations after calibrations. The calibrated flow coefficient, C, for the simplified model varies between 0.57 and 0.64 with an average value of 0.62 for all fan frequencies.

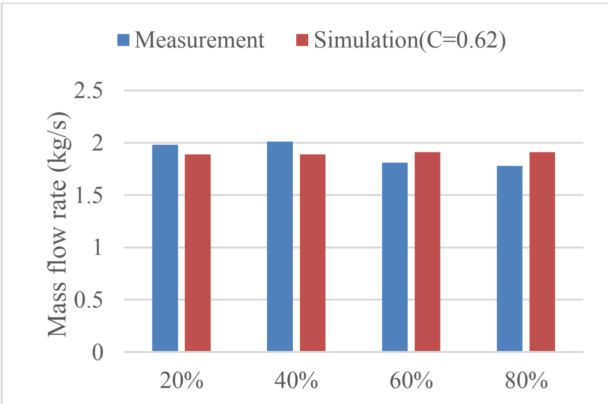

Figure 5: Inlet damper flow rates at the 5th floor for different roof fan frequencies (20% ~ 80%) and corresponding flow coefficients after calibration (Day 1)

With the average flow coefficient, the predicted mass flow rates through the inlet damper at the 5th floor were compared to the measured data in Table 3. The relative difference is within 4% and 7%.

Table 3: Predicted and measured mass flow rates through the damper at the 5th floor for different frequencies of the roof fan.

VFD of roof fan	20%	40%	60%	80%
Measured data (kg/s)	1.98	2.01	1.81	1.78
Predicted result (kg/s)	1.89	1.89	1.91	1.91
Relative difference	4.5%	6.3%	4%	7%

Simplified model calibration in Day 2

With the average value of coefficient, $C = 0.62$, obtained from the calibration on Day 1, we simulated the whole building for Day 2. Figure 6 shows that there exists a significant discrepancy of up to 80% between the simulation results and the measurements. Therefore, the flow coefficient needs to be re-calibrated for the new weather and operating conditions for Day 2. The values of C of the inlet dampers were thus adjusted for each atrium section as shown in Table 4. After the re-calibration, Figure 6 shows that the simulated flow rates at the 5^{th}, 8^{th}, and 11^{th} floors were more uniform, and closer to the measured data than before the calibration.

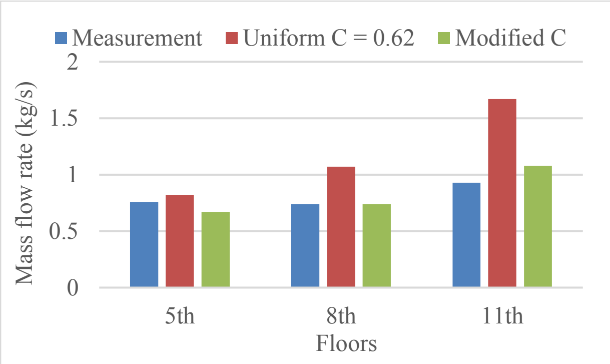

Figure 6: Inlet damper flow rates at different floors and the calibrations of the flow coefficients (Day 2).

Table 4: Modified value of flow coefficients, C, in the detailed CONTAM model (Day 2).

Section	1	2	3	4
Floor	4	5-7	8-10	11-13
Value of C	1.11	0.15	0.19	0.28

Comparison between detailed model and simplified model

Different from the simplified model that combines the three stories of each atrium into one zone, the detailed model simulates each floor as one zone, resulting in a total of 15 zones. Figure 7 compares the simulation results of the detailed and simplified models. Normalized root-mean-square deviation (NRMSE) is used here to quantify the difference between the two models (Eq. 2) (Qi, Wang, and Zmeureanu 2017). $\dot{m}_{d,i}$ and $\dot{m}_{s,i}$ are the mass flow rates through the damper at i^{th} floor for the detailed model and simplified model. N is the total number of the sections modeled. A smaller value of NRMSE indicates that the results of the simplified model are closer to the detailed model. In this study, the calculated NRMSE is 0.014, showing that the results of the two models are very close. Therefore, the simplified model can be used to replace the detailed model as the hybrid ventilation model for the building's predictive control of the inlet damper openings in each atrium based on anticipated/predicted weather conditions.

$$NRMSE = \frac{\left[\frac{1}{N}\sum_{i=2}^{N}\left(\dot{m}_{d,i} - \dot{m}_{s,i}\right)^2\right]^{\frac{1}{2}}}{\dot{m}_{d,\max} - \dot{m}_{d,\min}} \quad (2)$$

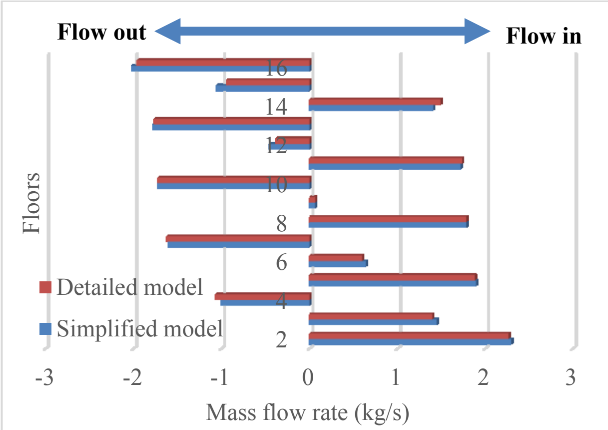

Figure 7: The comparison of predicted flow rates at the inlet dampers between the detailed and simplified models.

Discussion

To demonstrate the simplified model for potential use for predictive control applications, an example was used here for achieving evenly distributed natural ventilation flows through all the inlet dampers at different floors so as to naturally cool all 15 floors. This is realized by adjusting the damper opening areas.

Figure 8 presents the flow rates under the weather conditions of Day 1 for the fan frequency of 40% (i.e desired flow rate about 40% of maximum). It shows that the flow rate is quite non-uniform when all the dampers are fully opened. The flow rates of the 1^{st}, 2^{nd} and 5^{th} sections are much larger than the middle sections. In order to make all floors equally benefit from the natural cooling, it is preferred to distribute the inlet flow rates evenly by adjusting the damper opening sizes: reduce the opening percentage of the 1^{st}, 2^{nd}, and 5^{th} sections as shown in Table 5.

The effect of the optimization can be shown by quantifying a non-uniformity factor of the flow rate, the non-uniformity coefficient, k, as defined by Eq. (3) (Lian and Qi 2009). Here, $\overline{\dot{m}}$ is the average flow rate through the dampers at different floors; N is the total number of the sections modeled. A better uniformity of the flow among all inlet dampers means a smaller value of k. It is found that the value of k drops significantly from 0.74 before the optimization to 0.06 after the dampers opening sizes are adjusted. Therefore, the optimization of the damper opening area is an effective approach to achieve uniform natural ventilation flow among dampers at different floors.

$$k = \frac{\sigma}{\bar{\dot{m}}} \qquad (3)$$

$$\text{where } \sigma = \sqrt{\frac{\sum\left(\dot{m}_i - \bar{\dot{m}}\right)}{N}}$$

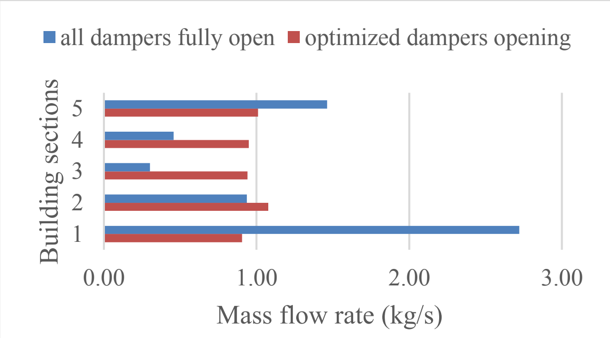

Figure 8: Comparing the natural ventilation inlet flow rates when all dampers are fully opened and when the damper openness are adjusted for achieving better uniformity at fan frequency 40% (Day 1).

Table 5: Damper opening percentage after the optimization.

Section	1	2	3	4	5
Floor	3	5-7	8-10	11-13	14-16
Day 1	15%	45%	100%	100%	40%

Conclusion

This paper reports a series of full-scale measurements of hybrid ventilation in a 17-story institutional building and associated whole-building simulations using both a 15-zone detailed and a 5-zone simplified multizone models. Full-scale measurements were conducted in two different days with significantly different ambient weather conditions. Mechanical fan flow rates at different fan frequencies, mass flow rates through dampers at different floors, outdoor temperature and wind conditions were measured. The simplified model of the whole building was calibrated by the measured data for both days. The simulated results were also compared to a detailed model of the building using CONTAM. To illustrate the optimization of the high-rise hybrid ventilation system using the simplified model, an example was also provided.

This study shares many important experiences of full-size high-rise building measurements and whole-building simulations. For example, it is found that the variations of weather conditions and their dynamic interactions with hybrid ventilation systems can be accounted for by flow coefficients in the simplified model of the building. Although the simplified model only needs five zones, the difference of the predictions between the detailed and simplified models is within 10%, indicating that it is possible to model the whole building in a simple way for the future on-line model-predictive control (MPC) applications of this high-rise building. The demo case study in the discussion section shows that the optimization of the damper opening area is an effective approach to achieve uniform natural ventilation flow through dampers at different floors.

Future studies are needed to implement the simplified model for actual on-line MPC applications of the building. The simplified model will also be further developed to include energy balance calculations for thermal mass analysis for future MPC applications of thermal storage for the building. More measurements are expected in 2017 to collect more data under different weather conditions, which will be used for the further analysis of hybrid ventilation systems in high-rise buildings and validation of the simplified model with energy balance equation.

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References

Brohus, H, C Frier, P Heiselberg, and O J Hendriksen. 2003. “Measurements of Hybrid Ventilation Performance in an Office Building.” *International Journal Of Ventilation* 1 (November). doi:10.1080/14733315.2003.11683646.

DOE. 2012. *2011 Buildings Energy Data Book*.

Dols, W Stuart, and Brian J Polidoro. 2015. *CONTAM User Guide and Program Documentation*. Gaithersburg, MD: National Institute of Standards and Technology.

Hu, Jianjun, and Panagiota Karava. 2014. “Model Predictive Control Strategies for Buildings with Mixed-Mode Cooling.” *Building and Environment* 71. Elsevier Ltd: 233–244. doi:10.1016/j.buildenv.2013.09.005.

Karava, P., A. K. Athienitis, T. Stathopoulos, and E. Mouriki. 2012. “Experimental Study of the Thermal Performance of a Large Institutional Building with Mixed-Mode Cooling and Hybrid Ventilation.” *Building and Environment* 57. Elsevier Ltd: 313–326. doi:10.1016/j.buildenv.2012.06.003.

Lian, Zhiwei, and Dahai Qi. 2009. “Modification for Evaluation Indexes of Air Distribution.” *Journal of Chongqing University* 32 (8): 937–942.

Malkawi, Ali, Bin Yan, Yujiao Chen, and Zheming Tong. 2016. “Predicting Thermal and Energy Performance of Mixed-Mode Ventilation Using an

Integrated Simulation Approach." *Building Simulation* 9 (3): 335–346. doi:10.1007/s12273-016-0271-x.

Menassa, Carol C., Nathan Taylor, and John Nelson. 2013. "Optimizing Hybrid Ventilation in Public Spaces of Complex Buildings - A Case Study of the Wisconsin Institutes for Discovery." *Building and Environment* 61: 57–68. doi:10.1016/j.buildenv.2012.12.009.

OEE. 2011. "Secondary Energy Use by End-Use." *Office of Energy Efficiency (OEE) of Natural Resources Canada (NRCan)*.

Qi, Dahai, Liangzhu Leon Wang, and Radu Zmeureanu. 2014. "Verification of a Multizone Airflow and Energy Network Model by Analytical Solutions to Stack Driven Flows in Buildings." In *eSim 2014*, 8. Ottawa, Canada.

Qi, Dahai, Liangzhu Wang, and Radu Zmeureanu. 2015. "Modeling Smoke Movement in Shafts during High-Rise Fires by a Multizone Airflow and Energy Network Program." *ASHRAE Transactions* 121 (2).

Qi, Dahai, Liangzhu Wang, and Radu Zmeureanu. 2017. "The Effects of Non-Uniform Temperature Distribution on Neutral Plane Level in Non-Adiabatic High-Rise Shafts During Fires." *Fire Technology* 53 (1). Springer US: 153–172. doi:10.1007/s10694-015-0554-2.

Turner, William J N, and Hazim B. Awbi. 2015. "Experimental Investigation into the Thermal Performance of a Residential Hybrid Ventilation System." *Applied Thermal Engineering* 77: 142–152. doi:10.1016/j.applthermaleng.2014.12.026.

Tzempelikos, Athanassios, Andreas K. Athienitis, and Panagiota Karava. 2007. "Simulation of Facade and Envelope Design Options for a New Institutional Building." *Solar Energy* 81 (9): 1088–1103. doi:10.1016/j.solener.2007.02.006.

Venticool. 2016. "IEA EBC Annex 62: The IEA Project on Ventilative Cooling." *EBC*. http://venticool.eu/venticool-home/.

Walton, George N, and W Stuart Dols. 2013. *CONTAM User Guide and Program Documentation*. Gaithersburg, MD.: National Institute of Standards and Technology.

Yuan, Sophie. 2016. *A Study of Hybrid Ventilation in an Institutional Building for Predictive Control*. Montreal: Master degree thesis, Concordia University.

Yuan, Sophie, Andreas Athienitis, Yuxiang Chen, and Jiwu Rao. 2016. "Development of a Thermal Model for Thermal Mass Coupled with Hybrid Ventilation in an Institutional Building." In *eSim 2016 Conference*, 10. Hamilton, ON, Canada.